national accelerator laboratory

TM-188
0452

SOME ASPECTS OF THE MAIN-RING BEAM SCRAPER PROBLEM

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September 3, 1969

1. Introduction

There are unavoidable beam losses in any accelerator. These cause radiation damage and maintainance problems due to the induced radioactivity. The NAL plan, not very well formulated is to concentrate as much as possible of this loss by means of beam scrapers. Ranft[1], in a series of papers, presents calculations on scrapers both from the point of view of the types of losses to be taken care of and the means for doing this. He points out that scrapers have been used at the CERN PS, but that they now prefer to spread their losses out. This is a point of view similar to that of the sanitary engineer who believes the problem is solved if he has adequate dilution. The advantage of using scrapers, if they can be made to work this way, is that they would be of radiation resistant materials (in contrast to magnet coils), and should need little or no work on them after installation, so that personnel may be protected from concentrated radioactivity by shielding.

Ranft's calculations[1] predate the invention of the wire septum (although he does calculate the effects of the septum shield made of tungsten wires). He therefore has too much lost beam, and the properties of the lost beam are not the same as will exist in fact. There is much to be learned, however, from reading his papers. They are the only written reports I know of which really bear on the design of beam scrapers in an ultra-high energy accelerator.

2. Mechanisms of Beam Loss

Beam scrapers can only be expected to take care of minor beam losses. Gross control malfunctions, etc., which could dump the entire beam, must be handled by an "abort" system. The beam losses which should be routinely taken care of by beam scrapers are a very small fraction of the total injected beam.

The primary reason for the location chosen for the scrapers is the possibility of beam loss from synchronous stability, due to problems at transition, longitudinal space charge beam blowup, noise in the accelerating voltage, etc. These effects are very hard to estimate. The one discussed most frequently is the possibility of trouble at transition. I understand that the beam losses at transition at CERN are undetectable with a monitor with a least count of better than 0.1%, and that the losses at the Brookhaven AGS, while visible on spill monitors, cannot be seen on the beam sensing electrodes due to masking by bunch shape changes. The recent success at CERN in the use of rapid ν jumping to avoid space charge effects at transition appears to me to largely eliminate the possibility of problems at transition in the main ring. Of course there will always be some mis-handling of the beam by the r.f. system, but the total amount of beam loss due to this cause should be very small. There is no beam capture problem provided the equipment is working. If it is not, then the problem is one for the abort system.

Scattering of the protons by the residual gas in the beam pipe can cause beam losses. Multiple coulomb scattering causes an enlargement of the beam, with a small "tail". The effect is small - at a pessimistic 10^{-7} torr, the rms multiple scattering angle is but 0.2 mrad which adds, in quadrature to the betatron oscillations injected, only 1 - 2 mm, a negligible effect. There is also nuclear scattering. Coherent scattering dominates, with a rms angle of about 0.3 mrad at 200 BeV, 7.5 mrad at 8 BeV. The total elastic cross-section is about 0.1 b, essentially energy independent. About 10^{-5} of the beam will be thus scattered. That scattered at low momentum will virtually all go into the magnets - distributed quite uniformly around the ring. Similarly, the inelastic collisions with gas nucleii, producing showers of particles at large angles (relatively) will distribute the resulting activity evenly. The total cross-section for this process is about 0.4 b, so that about 4×10^{-5} of the beam will be lost in this way. The beam scrapers can only eliminate the "halo" around the beam caused by those scattered particles which are not immediately lost to the walls of the vacuum pipe and magnets. This is in the neighborhood of 10^{-6} of the injected beam, so scarcely seems worth worrying about, but scrapers which locally reduce the machine aperture will, of course, capture some of these.

The invention of the wire septum by A. Maschke considerably reduces the number of scattered protons but this seems to remain the dominant source of particles for the scrapers to try to stop. Multiple coulomb scattering causes the protons to leave the septum so that they penetrate considerably less than all of the wires. The angles involved are small - .05 mrad or so, on the average. Still, an estimated 0.1% of the extracted beam will interact in the septum. The products of the inelastic interactions will have angles so large that virtually all of the particles will strike magnets before they reach a scraper. It has been suggested that a 2 - 3 ft. collimator in front of the B1 magnet just downstream from the septum would help protect that magnet, and further that a similar collimator, (with two holes, one for the external beam, one for the circulating beam) just in front of the last beam extraction septum magnet, could reduce the radiation damage. While these would help, the factor is not likely to be as large, one would like as many of the particles as possible to have angles which cause them to target on the inside of magnets. Ranft's calculations would appear to bear directly on this source of beam damage. His curves show 90% in the first magnet, 99% in the magnets which precede the field-free section of the long straight.

Measurements by Bellenttini, et al[2] show that the total elastic scattering cross-section for heavy elements is essentially equal to the absorption cross-section. Further, all of the scattering is coherent diffraction scattering, with an rms scattering angle for tungsten (interpolated from his measurements) equal to 0.19 mrad at 200 BeV. This angle is well within the acceptance of the accelerator. If there were no closed orbit deformations, those which did not strike magnets in the first half wave-length (i.e., all but the "tail" of the distribution) would be extracted three turns later, provided the aperture of the extraction system were adequate. The horizontal scattering amounts to a significant phase change (35° rms) of the betatron oscillation which is used to extract the beam, so that the operation of the extraction system would need to be evaluated. It seems better to attempt to catch as many of these particles on a scraper as possible. The first medium straight is 295° to 300° betatron phase advance from the electrostatic septum. This is close to the azimuth where the particles which just missed the septum on the inside cross the path of the particles which will extract on the following turn (see Figure 1). To avoid interference with the beam to be extracted on the following turn, the radial edge of the scraper must lie about 6 mm outside of the shadow of the septum. This does not catch as large a fraction of the scattering as one would like. A. Maschke pointed out that the scraper could have a notch (say, 5 mm high, 9 mm deep (horizontally)). The edge of the scraper could be adequately out of the aperture, say 3 cm from the centerline, and a 2.1 cm horizontal orbit bump could push the beam into the notch during extraction. In Figure 1, the dotted lines indicated the extent of the notch. The closed orbit is that with the bump on. Very little of the scattered beam would fail to strike this scraper. Alternatively the orbit bump could be less strong and the notch made higher, passing more of the scattered beam, but stopping all particles with large scattering angles and large betatron phase shifts. The uncaught protons would then be extracted with certainly no difficulty. It would not add to the problem of cleaning up external beam, as the amount of beam in the "halo" would not be greatly increased.

If the scraper in the first medium straight is dedicated to the catching of the scattering by the septum, then the other functions must be performed by scrapers in the other medium straights. For the latter, two should be sufficient. There is a point in separating these scrapers by two superperiods, so that the phase shift between them is an integral number of wavelengths plus an odd multiple of a quarter of a wavelength. Since the scraper in superperiod "A" operates on the outside, the others should scrape on the inside, to catch the particles lost from synchronous stability.

3. Structure of the Scrapers

Some aspects of the design of the scraper in superperiod "A" were discussed in the last section. There are other matters which need to be discussed.

One problem with scrapers or targets is the scattering of the beam out of them before it can interact. Scrapers which catch beam by moving the closed orbit slowly towards the scraper (or visa-versa) tend to have the beam strike very close to the inside edge. This makes the outscattering quite probable. Under some circumstances, a "lip" can make the beam strike the scraper farther from the edge, and thereby increase its efficiency. Unfortunately, these conditions do not seem to apply to the main ring. The only type of lip which seems worth considering is a very thin one of a high "Z" material, which uses multiple coulomb scattering to perform its function. If the particle striking the lip has an initial betatron amplitude which is comparable to, or larger than the amplitude which the lip scattering would induce, then the principal effect is to cause a phase shift, which is of little value. The conditions under which a lip can help is that the rms scattering angle in the lip is large compared with the angles characteristic of the betatron oscillations of the particles to be affected, and small compared with the acceptance of the accelerator. Further, the rate of approach of the closed orbit to the scraper must be very small. A Monte-Carlo type program originally written by A. Maschke showed that the lip which could do some good (the improvement is slight) at 200 BeV is a positive menace at 20 BeV. I would recommend that initial designs might use a lip so thin that it was appropriate for 20 BeV (just after transition), and that the 200 BeV problem simply be allowed to take care of itself. The scraper in superperiod "A" will have most of the particles striking several millimeters from the edge, so that outscattering will be no problem.

What I refer to as the scraper is the piece of material in which the beam particle makes a strong interaction. This is where a nuclear cascade starts, most of the particles of which make angles with the beam axis which are large compared with the accelerator acceptance, and large compared with coulomb scattering or nuclear elastic scattering. Here the length of the medium straights can be put to some advantage. The scraper itself should be as far upstream as possible. At the downstream end, a collimator will intercept a good fraction of the cascade. For a scraper with lots of beam hitting it, this collimator probably should be 6 feet or so of iron. The hole in it should be just large enough to clear the matched accelerator aperture. This is 1.4" x 3.2", and is a small solid angle seen from the scraper. There would seem to be little gained by making this collimator hole adjustable, or in worrying that its placement does not make full use of the magnetic orbit bump.

There is a question as to the best material from which to make the scraper. Ranft argues that the material should be low Z and low A (which fortunately come together). The idea is that outscattering due to multiple coulomb scattering is drastically reduced by low Z. Low A is important because heavy nucleii have elastic scattering cross-sections equal to their absorption cross-sections. In light nucleii, the elastic scattering is considerably less probable (a factor of 4 for carbon, 6 for beryllium). There is a factor which works the other way. Some of the protons which strike the scraper have negative values of $x' = dx/ds$. To avoid these being lost, the interaction mean free path should be as small as possible. In some Monte Carlo calculations I did, beryllium seems better than copper for 200 BeV and about the same for 20 BeV. Since this program does not consider nuclear elastic scattering, I believe that there is no doubt whatsoever that the material for the inside surfaces of the beam scraper should be as light as possible. This only applies to the first two or three millimeters. There would be a considerable advantage in the shielding provided by heavy materials in the outer regions.

The scraper should be adjustable, so that the amount of aperture it defines can be geometrically controlled. If the scrapers other than the one in superperiod "A" both scrape on the inside, and, say on the bottom, (i.e. each is "l" shaped), then simply mounting them on the standard magnet stands with relatively long vacuum bellows connecting them into the system will allow the needed adjustment of the amount they protrude into the aperture. It seems worthwhile even with magnetic orbit bumps to have the geometrical aperture as small as good operation will allow. The scrapers themselves need not be more than five feet long - maybe less. The vacuum seal should be make well outside the region of primary interaction, to avoid the possibility of damage by a fast beam dump. The power delivered to the scraper is so small that cooling should not be needed. The collimator at the downstream end of the medium straight is simply aligned with the magnet axis. Probably some adjustment of the scraper which catches the septum scattering (it is really more of a collimator) should be provided, as this may be easier than adjusting the vertical orbit position at full energy so that it exactly passes through the notch.

The aperture needed at high energy is reduced by damping of the betatron oscillations. To make the scrapers define a smaller aperture, the orbit can be deformed locally by magnets which move the closed orbit closer to the scraper. If there were a "halo" on the beam which one wished to remove before starting the extraction process, the bumps could move the closed orbit very close to the scrapers to do the trimming. To avoid disturbing the orbit in other portions of the accelerator, the bump must be made with three magnets (the spacing of a two magnet bump must be exactly a half wavelength). If one bump magnet is located one station away from the scraper upstream, another similarly placed downstream and one in the medium straight itself, the strengths needed are 1.6 mrad for the two end horizontal magnets, 1.4 mrad for the middle one. These could be considerably reduced by separating the outer magnets more, so that the bump spans 140° of phase advance; 0.57 mrad and 0.35 mrad, respectively. These allow a 5 cm displacement at the beta-max horizontal position of the scraper. Vertically, at beta-min, 1.6 cm should be sufficient. The short bump requires a 0.5 mrad for the outer, 1.5 mrad for the inner magnet. The long bump requires more power in the outer magnets, 0.6 mrad, with 0.4 in the inner one.

These magnets must be connected to programmed or programmable power supplies, either in series with their strengths in the correct ratios, or to separate supplies with the computer properly matching their strengths. They must be water cooled magnets, as there is not space for low field magnets which will produce these deflections (22kG-ft/mrad).

4. Shielding

With the assumption of 0.1% of the beam being absorbed in the septum, and 0.1% therefore elastically scattered, the scraper in the first superperiod will have a beam power of 200 watts incident upon it. M. Awschalom's curves then show that with two feet of iron around the interaction region the radiation level (residual after long bombardment) will be of the order of 0.5 roentgen/hour at the surface of the shield. This is tolerable, as there is a further reduction by $1/r$ or $1/r^2$ as one goes away from the shield, and passersby do not spend much time in the field. If the septum turns out to be less efficient, more shielding would be desirable, and there could well be a space problem.

The architectural design of the medium straight section leaves something to be desired. The enlarged section which extends only to the ends of possibly slightly bulky shields does not help the tunnel vehicle to pass, as its turning radius and length are too great. Thus the increased size seems wasted. Further, the outside of the scraper does not need shielding for personnel, so that the centerline could be offset to further increase the passageway, but this would be useful only if the length were about doubled.

M. Awschalom worries about the radioactivation of the ground water. His numbers indicate a possible problem, with power of this magnitude, but other laboratories with similar amounts of power either are unaware of the problem, or ignore it, or it does not really exist. It seems that there should be ways to reduce the amount of percolation to an acceptable level. Alternatively, the floor in the medium straight could be poured on top of a few feet of low grade concrete and the backfilling around the tunnel walls made of a similar material to keep the water-permeated material farther from and better shielded from the scrapers.

5. Acknowledgements

I do not pretend that this report represents my own work. I have collected ideas and data from many people in the laboratory. I cannot remember just who clarified which aspect of my thinking, so that the credit must be very general. I tried to talk to as many people as time would allow and gather together their ideas. Needless to say the discussions seem barely to have gotten started. The opinions, however, are my own.

REFERENCES

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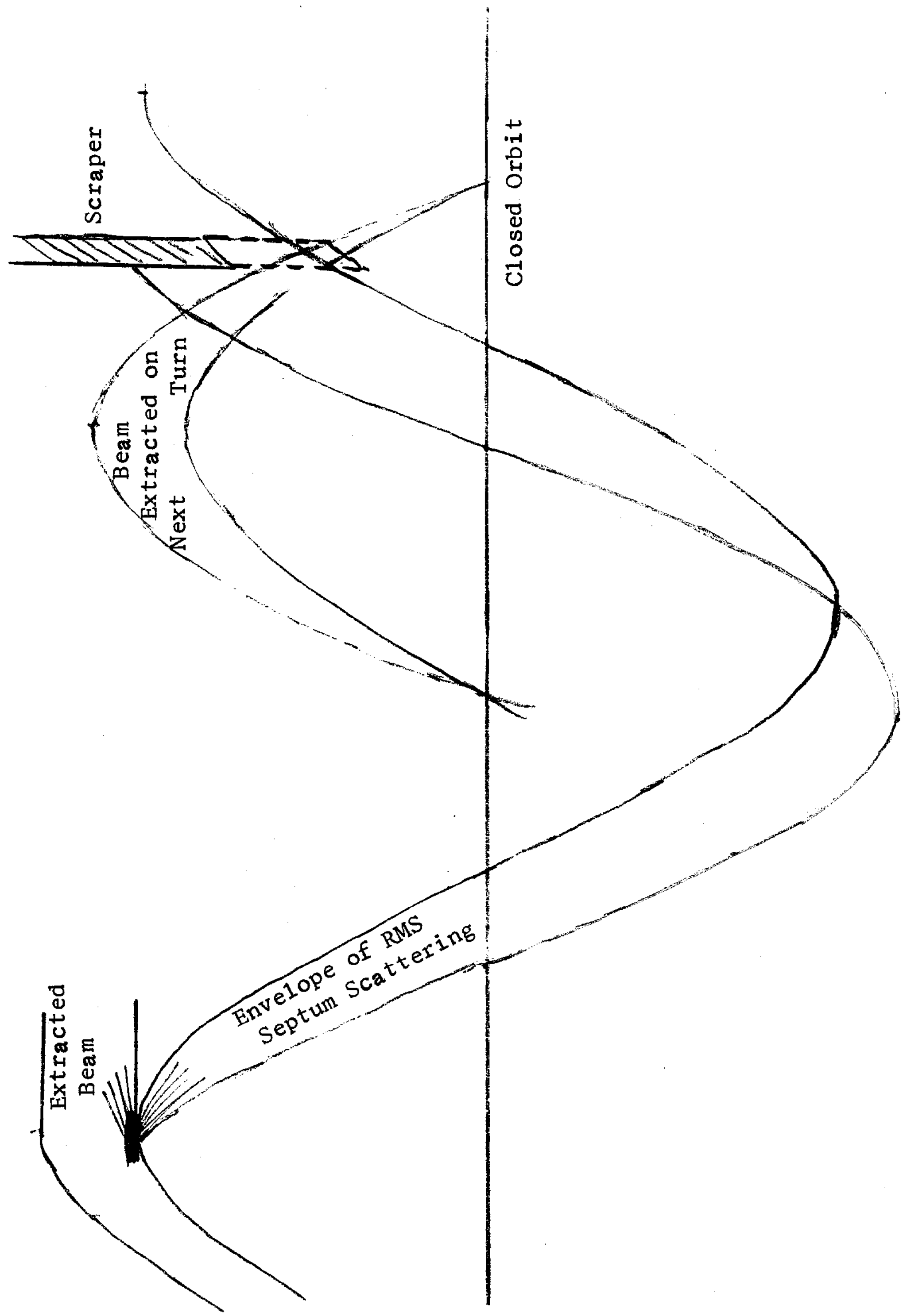

Fig. 1. Proton Paths Between Septum
and Scraper